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FULL LENGTH ARTICLE

Investigating the role of polymer type and dead end pores' distribution on oil recovery efficiency during ASP flooding

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Abstract Although alkaline-surfactant-polymer flooding is proved to be efficient for oil recovery from petroleum reservoirs, effects of existence of dead end pores on this process need more discussions. In this work, several ASP flooding tests constituted from 4 polymers, 1 surfactant and 1 alkaline were performed on micromodels designed in four various dead end pore distributions initially saturated with crude oil. The results showed that although using ASP solution constituted from hydrolyzed polymers at high molecular weights significantly increases oil recovery factor due to increasing apparent viscosity of the solution, using sulfonated polymers in ASP solution increases oil recovery much more because of their capability to increase viscosity even in saline solutions. In addition, it was concluded that the number of dead end pores as well as their distribution with respect to the flow direction are two main characteristics that identify the efficiency of brine and ASP floods in dead end porous media. Moreover, although in ASP flooding, since the viscosity is higher and the front is flatter, the role of the number of dead ends on the recovery efficiency is more identifiable than the role of dead ends' distribution, in waterflooding, since the mobility ratio is not low enough, the role of dead end direction with respect to the flow direction plays a more significant role in recovery process. So, considering the efficient direction of injection is too important during waterflooding and chemical EOR especially in reservoirs that have a remarkable percentage of dead end pores in their geological structure.

1. Introduction

Chemical flooding, in particular alkaline-surfactant-polymer (ASP) flooding, has attracted remarkable interests because of current high oil prices and the need to increase oil production.

Surfactant flooding is a common chemical EOR which improves oil recovery significantly because of its crucial effect on decrease in IFT (interfacial tension) even in dilute solutions; however, it does not have good sweep efficiency. Although it

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could have good sweep efficiency in high concentrations which causes micelle flow, reaching to those concentrations of surfactant solution is not economical. Thus, it is better to add a relatively cheap co-surfactant as well as a viscosity improving agent in those surfactant solutions to make operations economical.

The alkaline flooding method relies on chemical reactions between chemicals such as sodium carbonate and sodium hydroxide (most common alkali agents) and organic acids in crude oil to produce in situ surfactant (soaps) that can lower interfacial tension. So, in heavy oil reservoirs which have high acid contents, using alkaline as co-surfactant is economical and can provide lower IFT seriously.

The main concept of polymer flooding is affecting the sweep efficiency. Sweep efficiency is defined as the ratio of oil volume contacted by displacing agent to initial volume of oil in place [1]. Sweep efficiency is affected by mobility ratio, pore structure, reservoir rock wettability, reservoir heterogeneity, fractures and properties of fractures [2]. Polymer solution increases oil recovery in three ways: (1) by affecting fractional flow, (2) by reduction of water–oil mobility ratio, (3) by diversion of injected water toward swept zones [3]. Although polymer flooding also in a common EOR method increases oil recovery by improving water viscosity and sweep efficiency, it does not improve oil recovery in dead end pores significantly. This method implied displacement mechanisms of visco-elastic polymer flooding such as pulling and stripping. Since much residual oil remains cohesive to tiny and dead end pores, using an IFT reduction agent is essential. The IFT reduction agent is surfactant; however, it may not be economical singularly. So, adding alkaline to the polymer and surfactant solution increases recovery by applying all displacement mechanisms of polymer flooding, surfactant flooding and alkaline flooding.

Surfactant whether synthetic or in situ surfactant generated by alkaline reaction with crude oil's acids, reduces IFT between water and oil [4]. Reduction in interfacial tension can result in capillary number which reduces residual oil to a low value in swept regions [5]. In addition to the use of alkaline and surfactant, polymers should be used to provide mobility control to the displacement process [6]. So, ASP flooding can increase oil recovery considerably.

Many surfactant-polymer flooding works were performed in 1970s [7,8]. Co-surfactant enhanced alkali flooding [9] was introduced which allowed increasing the optimal salinity of the alkali slug high enough for its satisfactory propagation. The phase behavior of oil-brine-surfactant systems would often be accompanied by viscous emulsion, gels or liquid crystals [10,8]. Most of the surfactant flooding in 1970s and 1980s were limited to sandstones with low salinity. Recent research has led to the development of surfactant systems suitable for high salinity and carbonate environments [11–14]. Sedaghat et al. [14] did many ASP experiment in fractured media but they did not survey it in dead end media. In addition, several ASP field tests have confirmed that residual oil can be displaced by the use of alkaline-surfactant-polymer [15,16]. The most famous tests have been done on Daqing oil field in which oil recovery has been increased 20% more than waterflooding [17]. Despite, numerous studies reported in this field, a little attention has been paid on the efficiency of ASP flooding in systems with dead end pores, especially when the models have different numbers and distributions of dead ends.

In this work, several ASP solutions constitute from 4 polymers, 1 surfactant and 1 alkaline type were used in flooding tests. And the effects of chemical type as well as effects of dead end distribution on oil recovery efficiency were investigated. To apply the defined distributions of dead end pores to the porous media, micromodel system was selected and used.

2. Experimental facilities

The micromodel set-up is composed of a micromodel holder placed on a platform. It includes: a camera with a video recording system, a pressure transducer and a precise low rate pump. Fig. 1 illustrates a schematic of the experimental setup.

2.1. Pumps

A "Quizx" pump with a high accuracy and low flow rate was used. This pump can inject the fluid with an accuracy of 10^{-5} to 10 ml per minute. In addition, a vacuum pump also was used to wash and clean the micromodel by distilled water and toluene.

2.2. Optical system

In these experiments a high quality camera which had the zooming ability up to 200 times was used. This camera is attached to computer by a line. During the experiments, pictures are taken in specified periods of time.

2.3. Image analysis

To analyze the results of experiments in micromodel, the saturation of fluids should be measured. In order to calculate the oil saturation in porous media, the fluids should have distinct colors. In this project we used Photoshop software to analyze the pictures and calculate the saturation of fluids by calculating oil pixels of image. To consider brownish parts of porous media which represent alkaline diffusion, a range of brownish colors were considered for saturations 0.25, 0.5 and 0.75. Average saturation of porous area is used to calculate oil recovery.

2.4. Micromodel preparation

First, the patterns which are synthetic porous media with defined characteristics were designed by Corel software and then were engraved by laser tool on glass. Schematics of micromodel patterns are shown in Fig. 2. Then the patterns of micromodel for acquiring proper depth were fused throughout the model.

Four models with different dead end distribution patterns were engraved on glass and then another glass was placed over it and covered the engraved pattern and created porous media. That glass which covers the surface of porous media has input and output holes which were drilled on it and injection and production of fluids flow through these holes. This set was placed in a special furnace that its heat flux was controlled automatically. Then furnace started from ambience temperature to 724 °C slowly and after that the furnace was cooled down to the ambience temperature. This heat process is called fusing which causes two glass plates of micromodel adhere to each other.

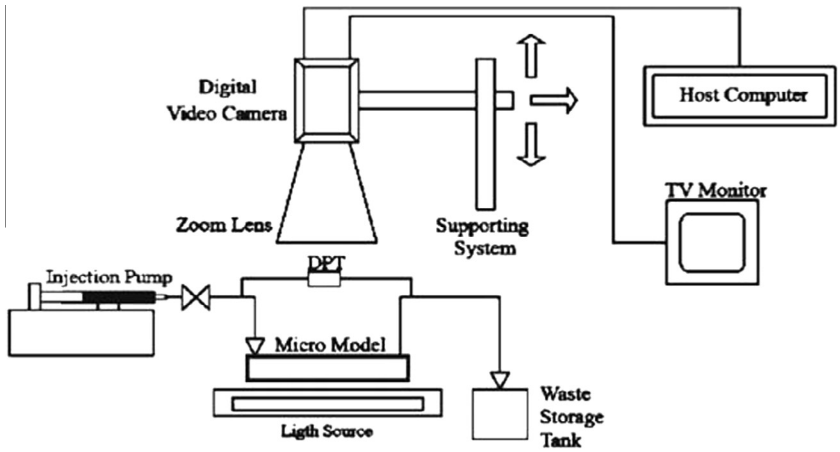

Figure 1 Schematic of micromodel set up.

Physical properties of two-dimensional models which are illustrated in Fig. 2 are given in Table 1. Because these models were in long time contact with toluene, they are completely oil-wet. This is due to toluene effect as an oily solvent to change wettability of glasses from water-wet to oil wet.

3. Fluid samples

Oil, brine and ASP solution are used in these experiments. Properties of each fluid are important in the experiments. These properties are explained in next sections.

3.1. Oil sample

This sample is taken from an Iranian oil reservoir and its properties are shown in Table 2.

3.2. Brine

Brine with concentration of 10,000 ppm and viscosity of 1.03 cp is used in the experiments. In addition to salt, other ionic compounds exist in reservoir water. Thus, other compounds were added to brine. Brine properties are illustrated in Table 3.

3.3. ASP solution

In the tests, four types of polymer, one type of surfactant and alkaline were used to produce 4 different aqueous ASP solutions: two kinds of 30% hydrolyzed polyacrylamide (HPAM 3330 and 3430), as well as AN 105 and AN 125 as sulfonated polymers were used, also an anionic surfactant, SDS, and an alkaline, Na_2CO_3, were used as respectively the most common surfactant and alkaline in chemical EOR. Pure chemicals used in this work are shown in Table 4.

In order to prepare ASP solution, pre-determined amount of surfactant and alkaline were added to a known amount of brine to produce a solution with a specific weight fraction. The powders/crystals are solved in water by stirring. After getting a homogenous and transparent solution, specific amount of polymer powder is added to a specific amount of water in order to produce a solution with a specific weight fraction. Then, this solution is kept in 58 °C for 12 h. ASP solutions are shown in Table 5.

Rheological behavior of these ASP solutions in various salinity conditions was measured and is shown in Table 6. The pH affected by Na_2CO_3 was measured 13.1 and IFT of ASP 1 with the oil affected by SDS was calculated 0.059 dyne/cm.

4. Experimental procedure

Before each experiment, the micromodel is cleaned by injection of toluene, acetone and finally distilled water. Micromodel patterns were saturated by oil. Then, injection fluids were flowed through the models in a constant flow rate of 0.0008 ml/min. During the tests, images were taken from the patterns in specific time steps. Tests finished after 2.5 PV injection, which normally displacements became stable with no significant changes in residual oil was detected. All tests were performed at ambience conditions and horizontally mounting.

5. Results and discussion

Four models with different distributions of dead end pores were used. In this section, effects of brine and different chemical floods on oil recovery efficiency in various dead end models were investigated.

5.1. Waterflooding

Oil recovery versus waterflooding for all four models is shown in Fig. 3. As it is obvious, waterflooding in model B leads to the highest oil recovery. It is because of the existence of dead end pores in the flow direction that results brine to pass the model in paths orthogonal to flow. On the other hand, in model A although the number of dead ends is 0, the fluid flows in the flow direction and since this fluid is water with a low viscosity, fingering occurs and there is no remarkable sweep efficiency in the orthogonal path. In the other words, dead ends in the flow direction play the role of microfracture existence in the orthogonal direction that delays breakthrough and increases oil recovery. However, in models C and D since dead ends are orthogonal to the flow direction, increase in the number of them results in decrease in oil recovery. For models C and D, and especially in D, existence of dead ends in flow paths plays the role of fractures in the flow direction. Although

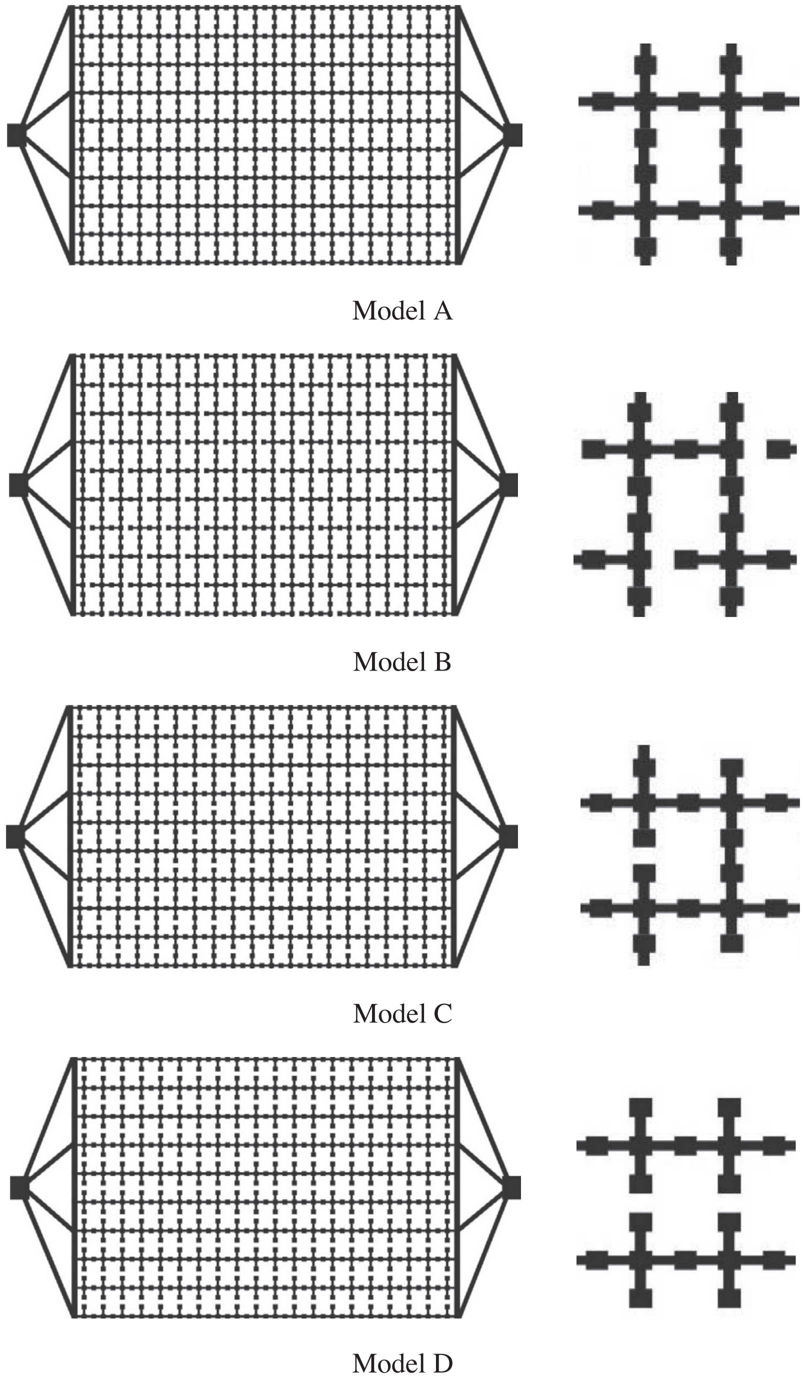

Figure 2 Schematics of micromodels with different dead end pore numbers and distributions.

Table 1 Micromodel pattern properties.

Pattern	A	B	C	D
Length (mm)	110	110	110	110
Width(mm)	70	70	70	70
Depth(mm)	0.2	0.2	0.2	0.2
Porosity (Φ)	0.134	0.130	0.130	0.130
Permeability (mD)	1300	1200	1400	1400
Pore to throat proportion	0.79	0.88	0.88	0.88
Number of dead ends	0	100	180	360

Table 2 Properties of oil sample.

Properties	Value
°API	29.3
Dynamic viscosity cp	20.01
Pour point °C	−22

the routes do not have higher permeability and are constituted from same pore and throat size, since existence of dead ends blocks fluid's way to pass the model in the orthogonal

Table 3 Synthetic brine composition.

Formula	Molecular weight (g/mol)	Concentration (g/lit)
NaCl	58.44	7
$Mgcl_2.6H_2O$	203.3	0.8
$Cacl_2.2H_2O$	147.03	0.2
Na_2So_4	142.04	2

Table 4 Chemicals.

Chemical	Molecular Weight (million Dalton)	Hydrolization (%)	Sulfonation (%)
HPAM 3430	12	25–30	0
HPAM 3330	8	25–30	0
AN 125	8	0	25
AN 105	6	0	5
SDS	288.38	–	–
Na_2CO_3	105.96	–	–

direction, water passes the model sooner than the other models. So, breakthrough occurs sooner and recovery decreases.

5.2. *ASP flooding*

Four ASP types constituted from four different polymers were flooded in four different models with different defined distributions of dead end pores.

5.2.1. *Role of ASP type*

To show the effects of injection of different ASP solutions on oil recovery, four ASP solutions were injected into the basic model, model A. Oil recovery versus injected pore volume is shown in Fig. 4.

According to Fig. 4, comparison of the results of ASP 1 and ASP 4 results in a conclusion that in a constant hydrolysis percentage, 25–30% for both HPAM 3330 and HPAM 3340, higher molecular weight leads to higher oil recovery. The molecular weights of HPAM 3330 and HPAM 3430 are respectively 8 and 12 million Daltons. So, the higher polymer molecular weight, the higher oil recovery is. It can be said that by increasing the molecular weight, viscosity increases and stabilizes the movement of fluid's front that increases the efficiency of sweeping process.

Comparing ASP 2 and ASP 3 in Fig. 4 shows the effects of using two different percentages of sulfonation of polymers i.e. AN 105 with 5% sulfonation and AN 125 with 25% sulfonation in ASP floods on oil recovery. It is obvious that by using AN 125 with 25% sulfonation percentage, the breakthrough time and oil recovery increase. Although AN 125 is a little heavier than AN 105, by comparing ASP 1 with ASP 4 that have

Table 6 Result of intrinsic viscosity at different temperatures and salinities.

Temp (°C)	Intrinsic viscosity (dl/g)			
0.1% Synthetic brine				
	ASP 1	ASP 2	ASP 3	ASP 4
20	16.28	22.57	16.01	18.86
40	15.95	22.14	15.82	18.57
60	15.62	21.72	15.58	18.28
80	14.30	20.30	14.21	18.00
100	13.99	19.98	13.34	17.72
1.0% Synthetic brine				
20	14.95	21.85	14.68	17.68
40	13.64	21.45	13.32	17.41
60	13.33	21.05	13.02	17.14
80	13.03	20.67	12.90	16.88
100	12.74	19.28	12.39	16.61

HPAM with the same molecular weight but no sulfonated groups it is shown that increase in oil recovery because of polymer molecular weight is not as much as that for sulfonated group existence. So, existence of sulfonated groups leads AN 125 to have such huge recovery in comparison with other polymers. Sulfonated polymers form molecular assembly which increases viscosity. Also, it should be considered that sulfonated polymers are resistant against salt. That is due to the presence of salt that contracts polymer molecules and reduces its viscosity. So, other polymers lose their capability to generate a viscous solution in salty water; however, AN 125 does not. Thus, this results ASP 2 to results in the highest oil recovery.

5.2.2. *Role of dead end distribution*

From previous section, ASP 2 resulted in the highest oil recovery. Fig. 5 shows oil recovery versus pore volume of ASP 2 injection into all patterns. Although as it was assumed, ASP results in higher recovery than water, but interestingly, here, the comparison is quite different from waterflooding results. As it is shown in Fig. 5, pattern A leads to the highest recovery. Although in waterflooding in pattern B the presence of dead end pores in the flow direction causes the fluid to pass the patterns better, in ASP flooding, since the ASP front is flatter, ASP moves slower and the mobility ratio is lower. So, fingering does not occur and ASP sweeps the whole area of model A efficiently and the presence of dead ends in the flow direction loses its effectiveness. Since the residual oil in dead ends get extracted harder and model B has a considerable number of dead end pores, the recovery in model B is seriously lower than in model A that has no dead end pores.

Model C has not only more dead end pores than model B, 80 more dead ends, it also has dead ends in the orthogonal to flow direction. So, the efficiency of oil recovery in model C is lower than model B as it is shown in Fig. 5. Furthermore,

Table 5 ASP solutions and used slugs.

Chemicals	Na_2CO_3 ppm	SDS ppm	HPAM 3430 ppm	HPAM 3330 ppm	AN 105 ppm	AN 125 ppm
ASP 1	10,000	2000	–	1200	–	–
ASP 2	10,000	2000	–	–	–	1200
ASP 3	10,000	2000	–	–	1200	–
ASP 4	10,000	2000	1200	–	–	–

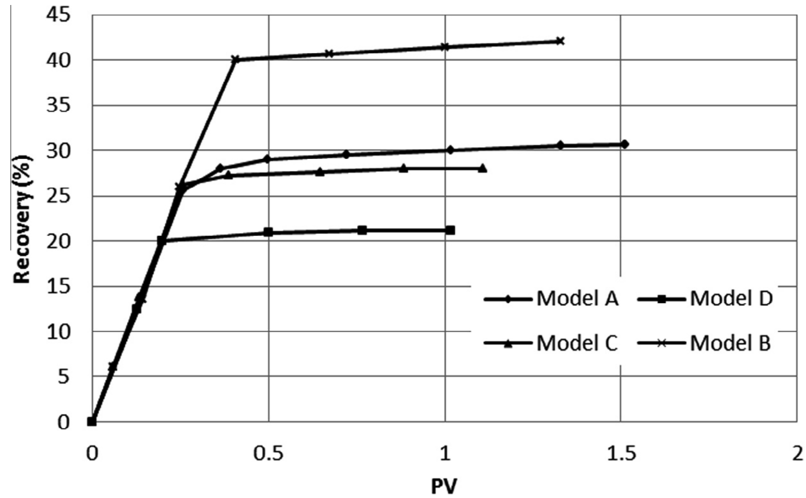

Figure 3 Recovery versus injected pore volume during waterflooding in all four models at the constant flow rate of 0.0008 ml/min.

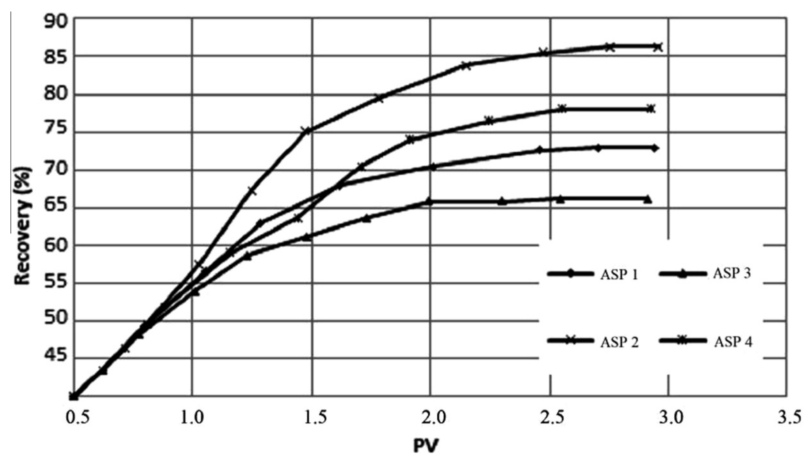

Figure 4 Recovery versus injected pore volume during ASP flooding in model A at the constant flow rate of 0.0008 ml/min.

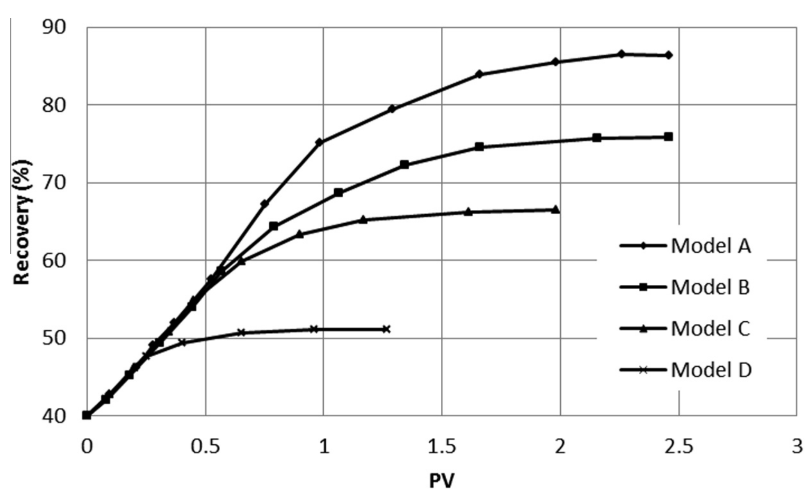

Figure 5 Recovery versus injected pore volume during ASP 2 flooding in all models at the constant flow rate of 0.0008 ml/min.

since model D has the most dead end pores all in the orthogonal to flow direction, 360 dead ends, the fluid would not pass other ways and passes the model faster. So, in model D, the breakthrough is sooner and the recovery is less than other models.

6. Conclusions

In this work, 4 ASP solutions with different polymer types were flooded in four dead end micromodel patterns. Based on the obtained results the following conclusions can be drawn:

- The numbers of dead end pores as well as their distribution with respect to the flow direction are two main characteristics that identify the efficiency of water and ASP flooding in dead end porous media.
- Although generally oil recovery efficiency decreases when a remarkable number of dead end pores exist in the medium, in waterflooding, the medium that have dead end pores in the flow direction has the most recovery, even more than a medium free from dead end pores.
- ASP solution constituted from heavier polymers leads to higher recovery due to increase in viscosity of the ASP.
- The most important feature of polymer that identifies ASP viscosity in saline basis is its sulfonation content. Higher sulfonation content leads to higher viscosity even in saline base. However, hydrolyzed polymers lose their viscosity with an increase in salinity.
- Since ASP has a higher viscosity and a flatter front in comparison with water, in opposite of the waterflooding, the role of the number of dead ends is more identifiable than distribution, direction, on the recovery efficiency.

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